MONITORING ROUTINE MINE SEISMICITY IN THE CONTERMINOUS UNITED STATES

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Sponsored by U.S. Department of Defense
Defense Threat Reduction Agency

ABSTRACT

We are applying standard U.S. Geological Survey/National Earthquake Information Center (USGS/NEIC) earthquake detection and location methodologies to monitor routine mine seismicity in the conterminous U.S. Our principal goal is to develop knowledge of mining seismicity in districts from which teleseismically recorded mining-associated seismic events might occur. This knowledge would provide a basis for understanding future seismic events from these mining districts that might be located by the International Data Center(IDC) after entry-into-force of the Comprehensive Nuclear-Test-Ban Treaty (CTBT).

Catalogs of routine U.S. mining events are available from May 1997 on the World-Wide Web (http://neic.usgs.gov/neis/mineblast/). Bulletins containing arrival time data are available by anonymous ftp (ftp://ghtftp.cr.usgs.gov/pub/mineblast/). Non-routine mining-events, such as unusually large rockbursts or longwall-collapses, continue to be listed in regular USGS/NEIC media (e.g., http://neic.usgs.gov/current_data.html) if they have magnitudes typical of felt earthquakes; they are not listed in the catalogs of routine mining events.

The cataloged epicenters are calculated from the arrival-times of seismic phases, and their accuracies vary according to the distribution of seismographic stations in the regions in which the mines are located. 90% confidence ellipses on epicentral coordinates are given with the data files on the ftp site. Although the USGS/NEIC does not obtain "ground truth" information from mining companies about most individual mining events, knowledge of mine locations and mining practices enables us to evaluate the reliabilities of the epicenters and confidence ellipses for many regions. The confidence ellipses represent location accuracies quite well for most of the mining districts. Plotting only events with small confidence ellipses dramatically reduces the scatter of epicenters. Problems with the mining-event confidence ellipses are typical of problems associated with confidence ellipses in general: the level of confidence associated with the ellipses must be viewed as being somewhat lower than the nominal 90%; there is evidence of substantial (up to 20 km) location bias for events in a few of the districts; ellipses associated with poorly recorded events are particularly prone to misrepresentation of location accuracy.

The magnitudes routinely assigned to the mining events are based on amplitudes of short-period secondary phases recorded at local and regional distances. For events occurring in the eastern and central U.S. (east of approximately 102 W longitude), the magnitude is the $m_b(L_g)$ magnitude. For events occurring in the western U.S., the magnitude is a local magnitude that is intended to be equivalent to the M_L magnitude developed by C. F. Richter for Southern California. Because these short-period magnitudes are computed with a different type of data than the teleseismic m_b that is commonly used as the short-period magnitude in the CTBT community, we have made a preliminary attempt to relate our M_L and $m_b(L_g)$ magnitudes to teleseismic m_b. For this we use formulas of Evernden (1967), appropriate for events occurring in western and eastern conterminous U.S. respectively, that enable the calculation of an m_b from regional P-wave amplitude/period data recorded in the U.S. Comparing our M_L with Evernden's "$m_{7.9}$" for western U.S. mining events suggests that our M_L is on average about 0.4 units lower than teleseismic m_b. Comparing our $m_b(L_g)$ with Evernden's "m_{eus}" for eastern U.S. mining events suggests that our $m_b(L_g)$ is also slightly lower, on average, than teleseismic m_b. These attempts to relate our M_L and $m_b(L_g)$ to teleseismic m_b must still be considered very approximate.

The largest magnitude {M_L or $m_b(L_g)$} that we have assigned to a routine mining event is 3.6. Coverage of the U.S. is currently not complete even in the magnitude 3.0 – 3.6 range.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **SEP 2000**	2. REPORT TYPE	3. DATES COVERED **00-00-2000 to 00-00-2000**
4. TITLE AND SUBTITLE **Monitoring Routine Mine Seismicity In The Conterminous United States**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Geological Survey,Adjunct US National Data Center,Denver,CO,80225**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S)
		11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Proceedings of the 22nd Annual DoD/DOE Seismic Research Symposium: Planning for Verification of and Compliance with the Comprehensive Nuclear-Test-Ban Treaty (CTBT) held in New Orleans, Louisiana on September 13-15, 2000, U.S. Government or Federal Rights.

14. ABSTRACT
See Report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

OBJECTIVE

Seismic events associated with the extraction of mineral resources potentially present both problems and opportunities for the implementation of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) (e.g., Heuze and Stump, 1999). The problems arise from the possibility that seismic signals from mine-associated events might be misinterpreted as being from small nuclear explosions. Opportunities arise from the potential of mine-associated events to calibrate the hypocenter determination and magnitude calculation procedures of the International Data Center (IDC). Many mine-associated seismic events are large explosions; the CTBT contains provisions for a State Party to provide information to the Technical Secretariat about the occurrence of large chemical explosions within its territory, as a "Confidence-Building Measure". Mining associated ground-failures present problems and opportunities similar to those presented by large mining explosions.

Explosions from surface mines and quarries and planned longwall collapses from underground mines are frequently detected in the conterminous U.S. by seismographs of the U.S. National Seismograph Network and other cooperating networks, and are recorded in near real-time at the United States Geological Survey National Earthquake Information Center (USGS/NEIC). The USGS/NEIC had historically dealt with routine mining events by identifying them at early stages of analysis and not analyzing them further. Since May 1997, in order to address the potential impact of mine seismicity on the CTBT, the USGS/NEIC has been preparing a monthly catalog entitled "Probable Mining Explosions in the United States" (for March 2000 and earlier) and "Routine Mining Seismicity in the United States" (after March 2000). We view these catalogs as providing a context for understanding U.S. mining-associated seismicity that might be located by the IDC after entry-into-force of the CTBT. The catalogs will also provide information to guide the selection of mines at which calibration experiments (e.g., Heuze and Stump, 1999) might profitably be conducted.

The catalogs are available on the World-Wide Web (http://neic.usgs.gov/neis/mineblast/) and associated bulletins containing arrival-time data and epicenter confidence ellipses are available via "anonymous ftp" (ftp://ghtftp.cr.usgs.gov/pub/mineblast/). Since October, 1999, our website has included a preliminary catalog, a preliminary bulletin with confidence ellipses and arrival times, and a map of routine mine seismicity, all for events occurring within the previous 61 days. Events are typically posted in the preliminary catalogs within several days of their occurrence: the analysis of the events is currently the responsibility of a single analyst, however, and the times to event-postings are longer than several days when the analyst is on leave.

The events listed in "Routine Mining Seismicity in the United States" are those that would have previously been ignored by analysts of the USGS/NEIC once they were identified as having the characteristics of day-to-day mine-associated seismicity. Atypically large longwall roof-collapses and non-planned mining-associated rockbursts and mine collapses have been, and continue to be, reported in regular USGS/NEIC earthquake catalogs if they have magnitudes that are typical of felt earthquakes. The USGS/NEIC receives independent information that some of these atypical events from mining districts are in fact associated with disturbances in mines; these events are then specifically identified in USGS/NEIC files as having been induced events. Atypically large mine-induced events that are not specifically identified as such to the USGS/NEIC will usually be listed as though they were tectonic earthquakes, even if they occur in a district that is known to have had previous mining-induced events. Unusual mining explosions have also occasionally been listed in the regular USGS/NEIC earthquake catalogs. Atypical mining events that are listed in regular earthquake catalogs of the USGS/NEIC are not listed in the catalogs of "Routine Mining Seismicity in the United States." Information on seismic events that have been listed in the regular earthquake catalogs of the USGS/NEIC may be obtained from the main USGS/NEIC website (http://neic.usgs.gov/).

Support for the early development of the catalog of routine mining seismicity was provided by the Arms Control and Disarmament Agency. Support for the ongoing cataloging of mining seismicity and improvements to the cataloging process is provided by the U.S. Department of Defense, Defense Threat Reduction Agency.

RESEARCH ACCOMPLISHED

Monitoring of routine mine seismicity

The epicenters listed in the "Routine Mining Seismicity in the United States" catalogs are calculated from the arrival times of seismic phases recorded at the USGS/NEIC. The completeness of the catalogs and the accuracies of epicenters listed in the catalogs depend on the locations of the recording seismographs with respect to the mines. The locations of seismographs situated within the contiguous U.S. that transmitted data to the USGS/NEIC in June 2000 are shown in Figure 1. The network of transmitting stations has changed somewhat during the period May 1997 – June 2000. In addition, individual stations sometimes have problems that make their data unusable. The completeness and accuracy of the mine-event cataloging therefore vary as a function of time for some of the regions.

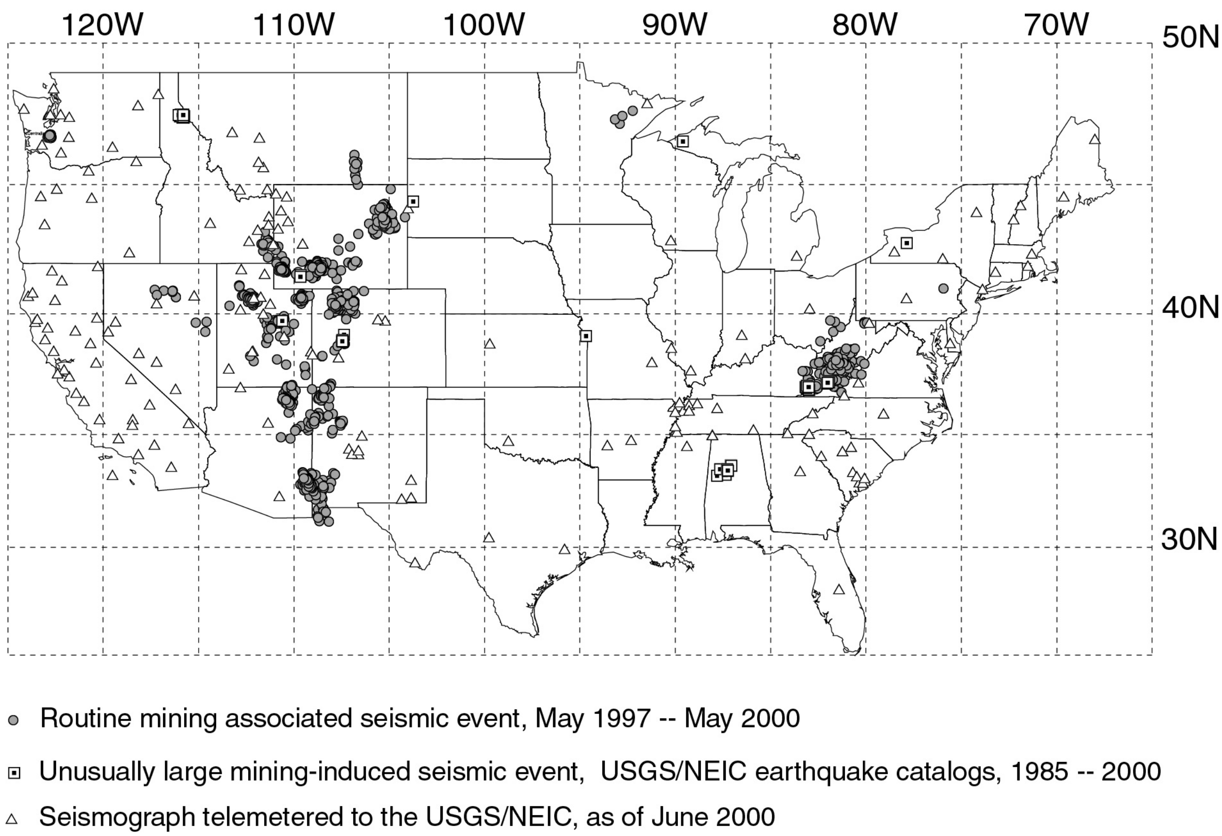

Figure 1. Epicenters of events listed in "Routine Mining Seismicity in the United States" and locations of large mining-induced events listed in regular earthquake catalogs of the USGS/NEIC.

In order to be cataloged, a mine-associated event must have been detected by the automatic event-detector and phase associator used at the USGS/NEIC (this has been the case for over 98 % of the events), or we must have obtained knowledge of the event independently of USGS/NEIC data.

The epicenters of mine-associated events are calculated from the arrival times of first-arriving P-waves, using the Jeffreys-Bullen travel-time tables (Jeffreys and Bullen, 1940). A large majority of arrival-time data used in computing the epicenters are of the P_n phase. Arrivals of the P_n phase from mine-associated events are commonly emersive and of low amplitude, so it is expected that there will be many more gross arrival-time errors than would be expected if arrival-time errors had a Gaussian distribution. Although later arrivals are not formally used in calculating the epicenter, analysts use time-intervals between P_g and S_g arrivals at regional distances to guide their picks of some P_n phases that would not otherwise be picked out of the background noise.

The magnitudes assigned to the events in the "Routine Mining Seismicity in the United States" catalogs are calculated from the amplitudes of local and regional seismic phases. The magnitudes assigned to events that occur east of the Rocky Mountains are $m_b(L_g)$ magnitudes (Nuttli 1973). The magnitudes assigned to events that occur in the western U.S. are M_L magnitudes computed according to the formula of Richter (1935). Unlike the M_L defined by Richter, however, our M_L(GS) are based on amplitudes picked from traces of vertical-component, electronically amplifying seismographs, rather than from the traces of horizontal-component, optically amplifying seismographs. Also, we compute M_L(GS) for seismic events from throughout the western United States, whereas Richter's formula was defined for Southern California, and implicitly incorporates the attenuative properties of Southern California crust and mantle.

The cataloged mining events are identified as such on the basis of their occurring in clusters that have similar sizes and waveforms and that are spatially close to active mining districts.

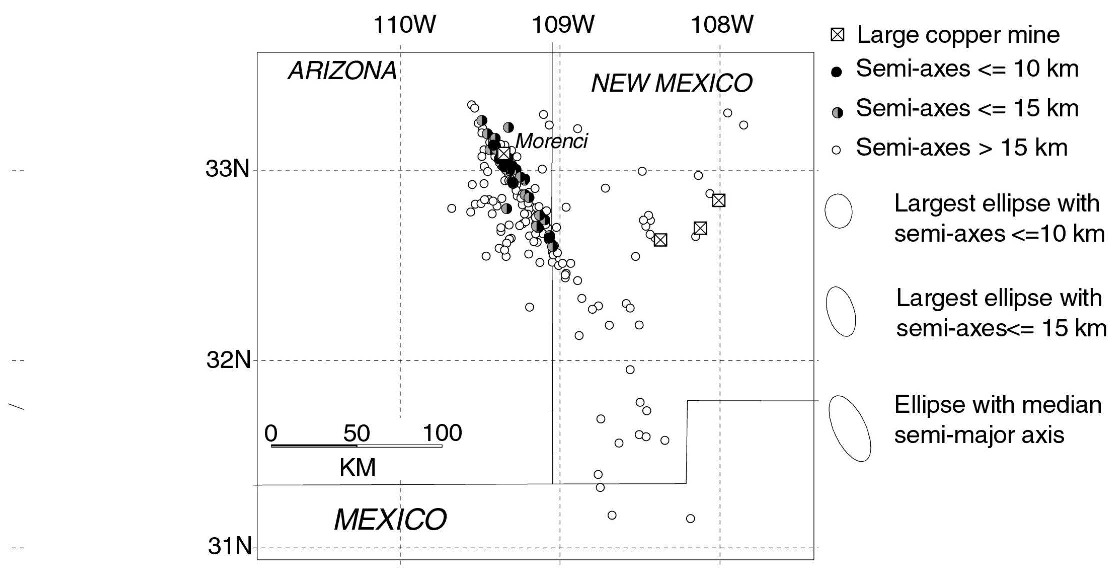

Figure 2. Mine-associated seismicity in southeastern Arizona and adjacent New Mexico. Most of these events probably occurred at Morenci, and many are severely mislocated. Epicenter symbols are distinguished according to the sizes of the associated 90% confidence ellipses.

Completeness of cataloging of mine seismicity

Our goal is to catalog mining events that are large enough that they might be cataloged by the IDC. Empirically, this would correspond to events of M_L(GS) ~ 2.5 in the western U.S. and events of $m_b(L_g)$ about 3.0 in the eastern U.S. We are not now attaining the desired level of completeness. It is noteworthy, for example, that we detected many mining events with $m_b(L_g) > 3.0$ in West Virginia in some months of our study, but none during protracted time-periods when key stations were not operating. In other regions, we have been able to locate some events only retrospectively, after they were reported in the Reviewed Event Bulletin (REB) of the Prototype International Data Center. Some of the initially missed REB events were actually quite well recorded by seismographs recording at the USGS/NEIC, but they were not found by the USGS/NEIC automatic event-detector. The events in northern Minnesota (Fig. 1), however, could be located only with arrival-time data listed in the REB; these events were recorded by only one of the USGS/NEIC stations. Conversely, some mining districts in the Mountain States are so well monitored by seismographs that we are able to locate many events that are substantially smaller than M_L(GS) 2.5. We deliberately catalog small events from such districts when such cataloging will help understand the nature of the districts' seismicity.

Accuracy of epicenters and the worth of confidence ellipses as measures of epicenter accuracy

Many of the large mines from which we record events are spatially well separated from other large mines, and some closely spaced mines occur in spatially well defined lineations. For these mines, we are able to estimate location accuracies and evaluate the confidence ellipses as measures of epicenter accuracy. The USGS/NEIC does not usually obtain "ground truth" information from mining companies about the locations of individual mining events.

For mines in the middle of regional seismographic networks in Utah and western Washington, it appears that ninety-percent of our epicenters are accurate to within 10 or 15 km. In contrast, for southeastern Arizona (Fig. 2) or southeastern Montana, on the fringes of the area covered by seismographs recording at the USGS/NEIC, an ellipse with a 100-km long semi-axis, centered on the mine, would be necessary to encompass ninety percent of the epicenters of events originating at the mine. Most of the severely mislocated epicenters probably result from a combination of poor azimuthal distribution of recording stations with respect to the epicenter and from gross errors in picking the P_n-phases whose arrival times are used in the epicenter determination process.

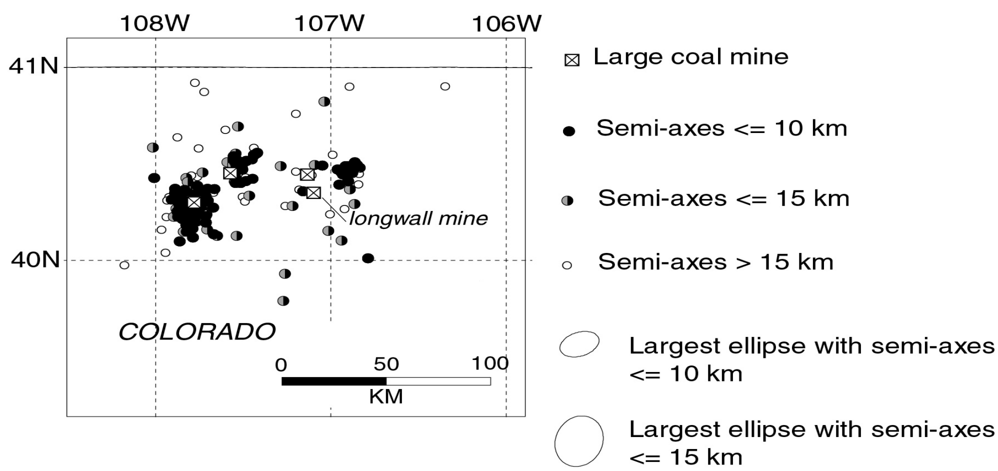

Figure 3. Mine seismicity in northwestern Colorado. With the exception of the longwall mine, the mines shown are surface mines. The longwall-mine events are those whose epicenters are calculated to lie near 40.45N, 106.90W, approximately 20 km ENE of their true positions. Epicenter symbols are distinguished according to the sizes of the associated 90% confidence ellipses.

The nominally 90% confidence ellipses associated with the calculated epicenters have the strengths and weaknesses that are typically associated with such confidence ellipses for events in regions of complex geology that are located with data containing non-Gaussian errors. The strengths are that the ellipses provide information on the relative precision of epicenters within a group of epicenters, and the highly eccentric ellipses do a good job of indicating the directions in which the associated epicenters are most likely to be mislocated (e.g., Fig. 2). The weaknesses are that the level of confidence to be associated with the ellipses is less than the nominal 90% and that the ellipses do not account for bias due to unmodelled velocity structure.

Figure 3 illustrates an intriguing example of bias. Planned roof-collapse events occurring in an underground longwall mine (Walter et al., 1996) are systematically mislocated about 20 km from their true source, whereas explosions occurring in two nearby large surface mines show much less, or no, bias. Such radical differences in bias within a small geographical area seem unlikely to be due to unmodelled velocity structure. The different biases may be due to systematic differences in interpreting phases from the explosion and roof-collapse sources.

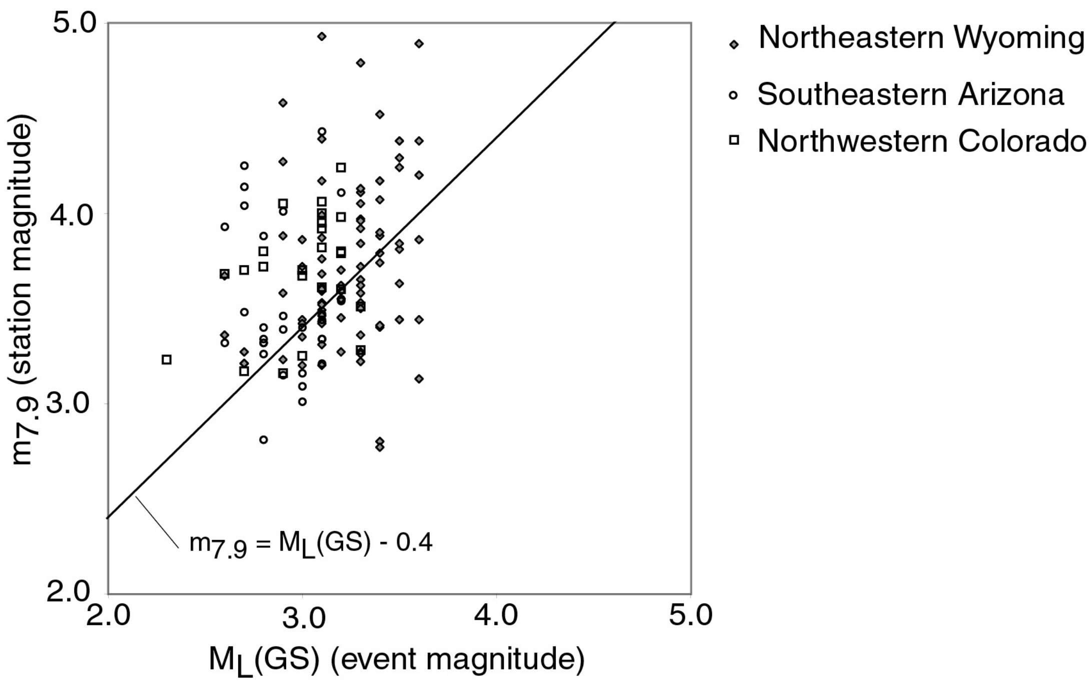

Figure 4. Regional P-wave $m_{7.9}$ (Evernden, 1967) for individual events recorded at individual stations, plotted as a function of the M_L(GS) assigned to the event. All $m_{7.9}$ were obtained at > 5 , and most at < 10 . Different symbols represent the regions in which the events occurred. The straight line is that of figure 5.

The relationship of $M_L(GS)$ and $m_b(L_g)(GS)$ to teleseismic m_b

The short-period magnitudes that we have assigned to the routine mining seismicity, $M_L(GS)$ and $m_b(L_g)(GS)$, are different than the teleseismic m_b that is the most commonly used short-period magnitude within the CTBT community. The $M_L(GS)$ and $m_b(L_g)(GS)$ are based on amplitudes of short-period secondary waves [S- or surface waves for the $M_L(GS)$ and surface waves for the $m_b(L_g)(GS)$] rather than short-period P-waves, and the $M_L(GS)$ was never explicitly calibrated to agree with teleseismic m_b. None of the events listed in "Routine Mining Seismicity of the United States" have been assigned a teleseismic P-wave m_b that is calculated according to standard USGS/NEIC procedures, because we did not have P-wave amplitude/period data for these events from USGS/NEIC stations at

> 15 . In order to examine how the M_L(GS) and $m_b(L_g)$(GS) should be interpreted in terms of the teleseismic P-wave m_b, we computed m_b values from P-wave amplitudes/periods recorded at epicentral distances of 5 < < 15 , using regionalized formulas of (Evernden, 1967) that were developed so as to yield magnitude values that are consistent on average with the USGS teleseismic m_b. The P-wave amplitude/period data at 5 < < 15 , used in the computation of short-period body-wave magnitudes according to Evernden's formulas, were extracted from arrival-time data files that are available at the WWW and ftp sites whose addresses are given above.

To western U.S. mining seismic events for which there are P-wave amplitude and phase observations at 5 < < 15 , we assigned Evernden's $m_{7.9}$, which was defined to give values consistent with teleseismic short-period P-wave m_b for events occurring in the western U.S. The individual values of $m_{7.9}$ show large scatter when plotted with respect to M_L(GS) (Fig. 4), but the $m_{7.9}$ are on average higher than the M_L(GS) values that were assigned to the respective mining seismic events. Taking the median value of the $m_{7.9}$ for each M_L(GS), for M_L(GS) having 10 or more $m_{7.9}$ observations in a single region, we find that $m_{7.9}$ are on average about .4 units larger than M_L(GS) (Fig. 5). Assuming that $m_{7.9}$ is an unbiased proxy for teleseismic m_b, figure 5 implies that teleseismic m_b will on average be about .4 units larger than M_L(GS).

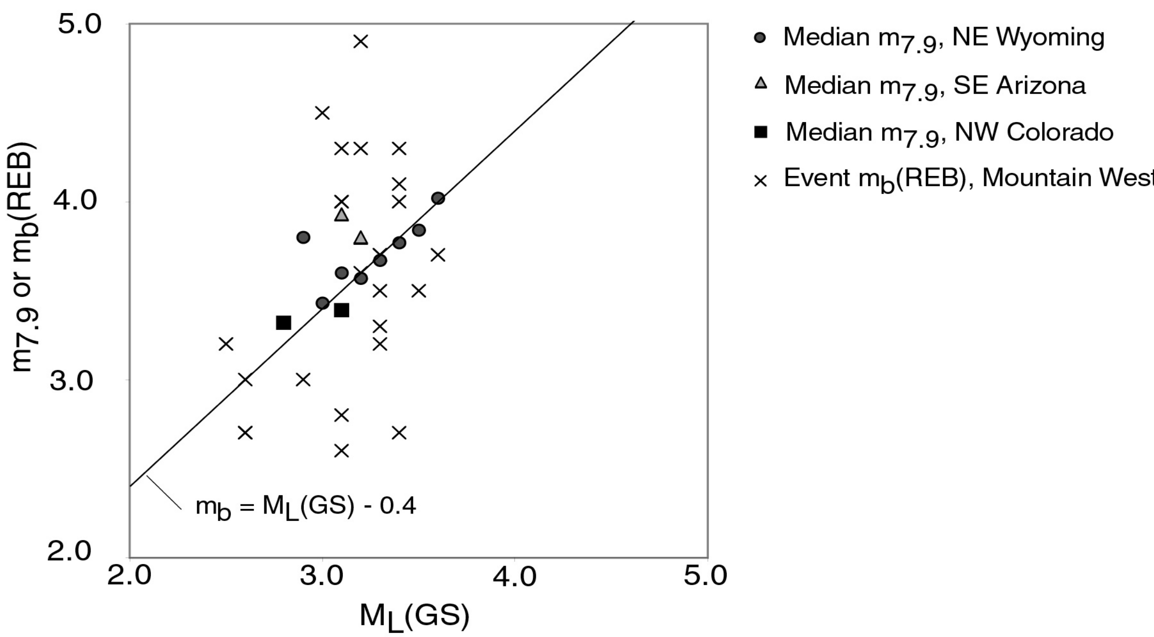

Figure 5. Body wave magnitude as a function of M_L(GS). Median $m_{7.9}$ are based on ten or more observations of $m_{7.9}$ (Evernden, 1967) for each value of M_L(GS). The straight line is an approximate fit by eye to NE Wyoming median values, assuming a slope of 1 for the relationship between $m_{7.9}$ and M_L(GS). The m_b(REB) are those reported for events in the Reviewed Event Bulletin of the Prototype International Data Center.

It would not be surprising if there were a systematic discrepancy between teleseismic m_b and M_L(GS) for the western U.S. mining seismicity. The M_L(GS) and teleseismic m_b have evolved along different paths from their common ancestor [Richter's (1935) original local magnitude], and the partitioning of an explosion's energy into P-waves and secondary waves is likely to be different than the partitioning of an earthquake's energy into P-waves and secondary waves. Keeping in mind the large scatter in the data of figures 4 and 5, and keeping in mind that the $m_{7.9}$ are measured at relatively few of the stations that recorded the mining-induced events, we regard the value of 0.4 as only an approximate measure of systematic difference between teleseismic m_b and M_L(GS) for the western U.S. mining seismicity.

The M_L(GS) appears to be an approximate predictor of the extent to which a regionally recorded mine event will be recorded by stations of the International Monitoring System and listed in the Reviewed Event Bulletin. Figure 6 shows an order-of-magnitude range of M_L(GS) over which Powder River Basin explosions might be listed in the REB, but the number of Powder River Basin explosions listed in the REB, as a fraction of the number of explosions listed in "Routine Mining Seismicity of the U.S.", increases generally as a function M_L(GS). A number of studies (e.g., Anandakrishnan and others, 1997; Carr and Garbin, 1998; Khalturin and others, 1998) have indicated that the maximum amplitude of secondary phases does not scale well with the total charge size of a ripple-fired explosion. Figure 6 suggests that the amount of energy from an explosion that goes into S- and surface waves at regional distances is somewhat indicative of the amount of energy that goes into teleseismic P-waves.

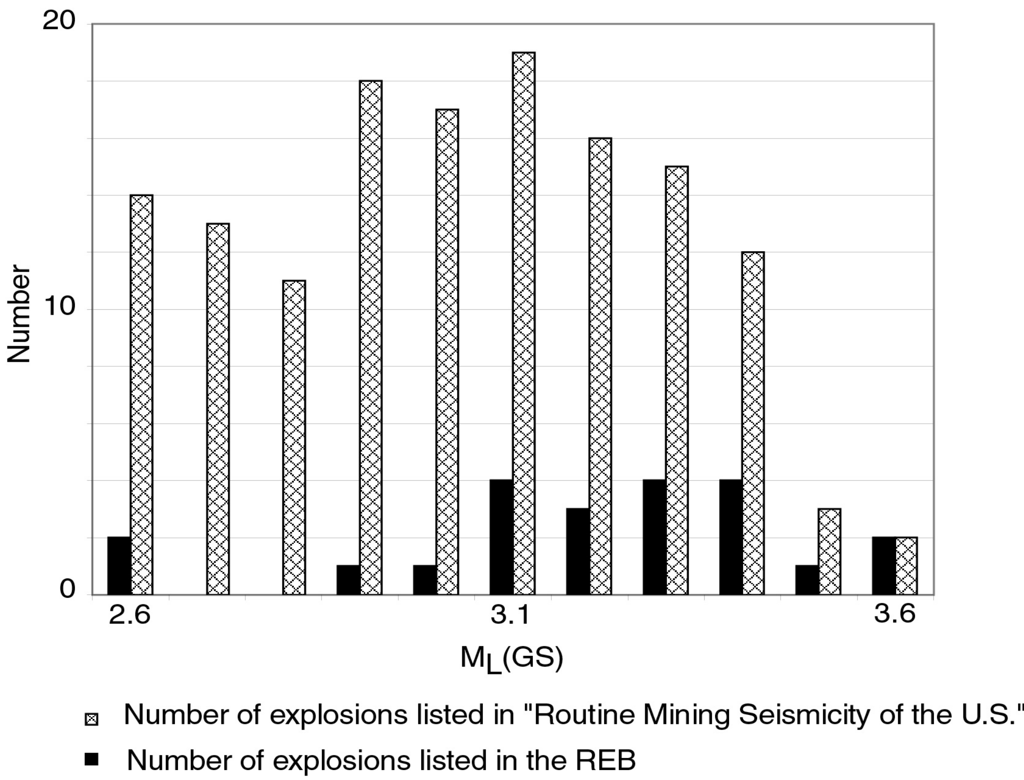

Figure 6. Numbers of events listed in the REB, as a function of M_L(GS), for explosions in the southern Powder River Basin, Wyoming, May 1997 through 20 February 2000.

The arrival-time data files that are available on our WWW and ftp sites contain a handful of P-wave amplitudes/periods from mining events in the eastern U.S., in the distance range 5 < < 15 , from which we can calculate m_{eus} (Evernden, 1967). The m_{eus} is defined so as to be consistent on average with the teleseismic m_b of the USGS for earthquakes in the central and eastern U.S. Assuming that the m_{eus} is an unbiased proxy for teleseismic m_b, the observations suggest (Fig. 7) that the $m_b(L_g)$(GS) may also, like the M_L(GS) in the western U.S., give values that are systematically somewhat lower than teleseismic m_b, but the number of observations is very few and most are from a single station. The $m_b(L_g)$(GS) is based on a formula of Nuttli(1973), which was defined so that $m_b(L_g)$ would yield values equal on average to teleseismic m_b for earthquakes in the central U.S. A discrepancy between $m_b(L_g)$(GS) and m_{eus} (or teleseismic m_b) might be due to differences in excitation of the L_g phase for explosions and earthquakes, or it might be due to attenuation of L_g phases in the central Appalachians being somewhat higher than in the central U.S.

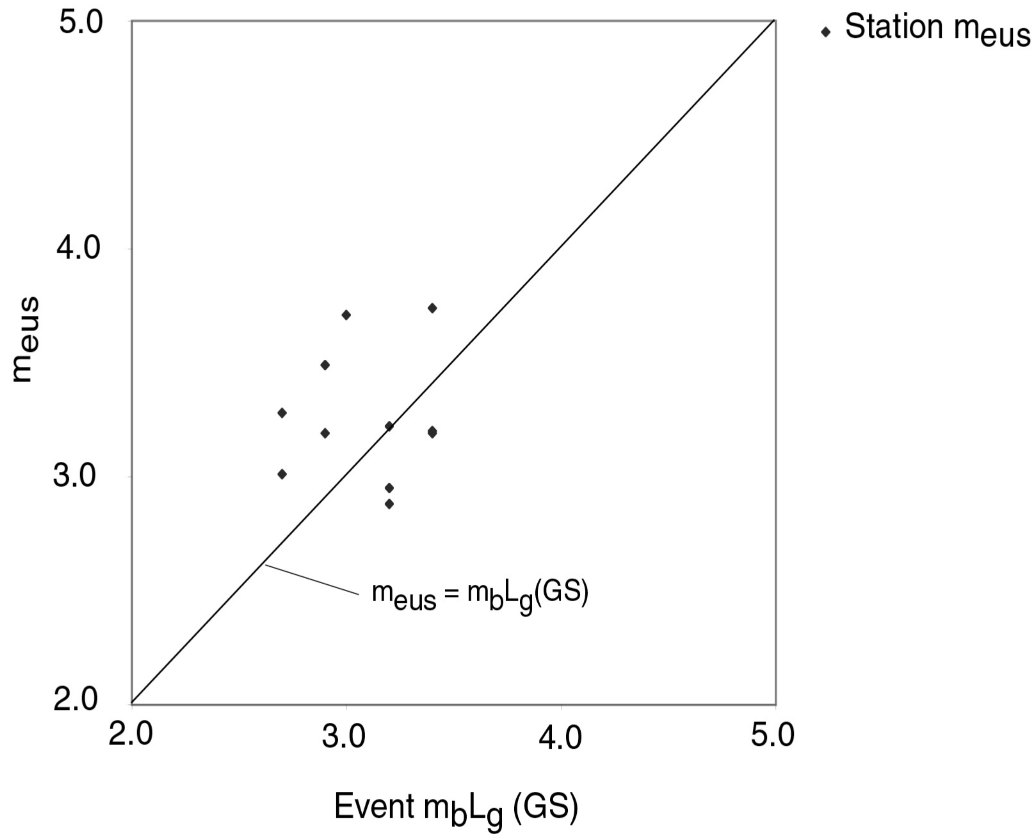

Figure 7. Values of individual station observations of m_{eus} (Evernden, 1967) plotted as a function of the event $m_b(L_g)$(GS), for mining events occurring in the eastern U.S. The line m_{eus} = $m_b(L_g)$(GS) is shown to facilitate comparison of the two magnitude types.

CONCLUDING REMARKS

Since May 1997, we have cataloged approximately 2,000 routine mining-associated seismic events in the U.S. and made the epicenters, epicentral confidence-ellipses, magnitudes, and arrival time data freely available on the WWW and on an anonymous-ftp site. The cataloging of these events provides a context for other States Parties to better understand the nature of U.S. mining-associated seismic events that will occasionally appear in bulletins of the International Data Center.

Our cataloging of mine seismicity has occurred during a time-period in which there have been significant changes in the network of seismographs that record at the USGS/NEIC. Future changes in U.S. seismograph coverage and USGS/NEIC procedures are likely to significantly improve the completeness of coverage and accuracy of epicenter location for regions in which completeness and accuracy are currently poor. These changes include installation of more seismographs in currently poorly monitored areas, improvement of the computer algorithm that automatically detects events and associates arrival-time data with events, and changes in the USGS/NEIC epicenter-computing algorithm that enable secondary phases to be incorporated explicitly into the location process.

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Key Words: Mining related seismicity, location, magnitude